Fiber Optic Based Optical Tomography Sensor for Monitoring Plasma Uniformity

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Abstract. A new type of fiber optic based optical tomography sensor has been developed for *in situ* monitoring of plasma uniformity. Optical tomography inverts optical emission measurements into the actual plasma distribution without assuming radial symmetry. The new sensor is designed to operate with only two small windows and acquire the necessary data in less than a second. Optical tomography is being tested on an ICP-GEC RF plasma source. Variations in plasma uniformity are measured as a function of different plasma conditions.

INTRODUCTION

In order to achieve shrinking critical dimensions with increasing wafer diameters, it is becoming increasingly important to monitor and control the uniformity of etching and deposition plasmas. Variations in the etchant concentrations within a plasma will have a significant impact on the final etching uniformity of a wafer [1]. Being able to measure and potentially correct plasma nonuniformities with the aid of an *in situ* diagnostic should reduce production costs and improve control over the critical dimensions on the wafer.

Optical tomography is one technique which could be used as an *in situ* plasma uniformity diagnostic. In optical tomography, line-integrated optical emission measurements are inverted to obtain the actual plasma distribution. This is accomplished without assuming the plasma exhibits radial symmetry, which is required with the simpler Abel inversion.

In order to demonstrate the potential application of optical tomography as a plasma uniformity monitor, a new fiber optic based sensor is being developed which could be used with commercial type plasma reactors. Optical access to these plasma reactors is typically limited to a few small diameter windows. In addition, the measurements need to be made quickly (<<1min) in order to be applicable to commercial plasma processes.

INVERSION ALGORITHMS

The restricted optical access to the plasma means that tomographic inversion routines typically used for medical x-ray tomography are not applicable. The resulting inversion problem is highly underdetermined since there are too few optical measurements to uniquely determine values for every point in the plasma. It is therefore necessary to incorporate some knowledge of the expected behavior of the plasma into the inversion process. This usually involves an implicit assumption on the smoothness or general shape of the plasma distribution.

Two different inversion algorithms have been investigated for use with the tomography sensor. The first method is based on Tikhonov regularization [2]. It is similar to a least squares fit, but with the addition of a smoothing norm. The distribution of emissivities are found which minimize the expression

$$\min_{\varepsilon}\left\{\left\|\left(\vec{A}\vec{\varepsilon}-\vec{I}\right)^{2}\right\|+\beta\left\|\left(\vec{B}\vec{\varepsilon}\right)^{2}\right\|\right\}$$

, where I_j is the intensity measured with fiber j, ε_i is the emisivity of pixel i, A_{ij} is the weighting factor for fiber j in pixel i, and B_j is the smoothing norm. The smoothing norm incorporates some of the expected plasma distribution behavior and is typically written in the form of a discrete differential equation. For the ICP-GEC RF

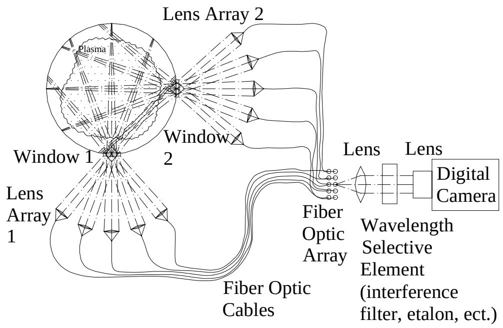


FIGURE 1. Schematic of the fiber optics based optical tomography sensor.

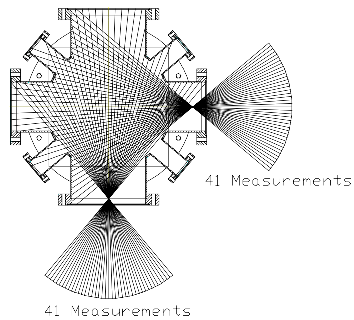


FIGURE 2. Observation geometry used with the ICP-GEC RF Reference Cell. The square represents the area used in the tomographic inversions.

Reference Cell, the smoothing norm assumes a radial inflection point and is defined as $\vec{B}\vec{\varepsilon} = (\nabla^2 + (C\vec{1} - \vec{R})K^2)\vec{\varepsilon}$, where $\vec{1}$ is the identity matrix, $\vec{R}$ is a diagonal matrix containing the distance of each pixel from the origin and the combined constant CK^2 is the smallest eigenvalue of the matrix $(\nabla^2 - K^2\vec{R})$. The regularization parameter, β, is determined by the L-curve criteria, which states that the optimum value of β will occur at the "corner" of the curve defined by a log-log plot of

$$\left(\left\| \left(\vec{A}\vec{\varepsilon}_\beta - \vec{I} \right)^2 \right\|, \left\| \left(\vec{B}\vec{\varepsilon}_\beta \right)^2 \right\| \right)$$

.

Although the Tikonov regularization algorithm works well, finding the solution involves the matrix inversion of a very large nonsparse matrix. This requires a significant amount of computational power, particularly when calculating the L-curve. Therefore, a new type of inversion routine is being developed which can be easily operated with only a desktop computer. The new technique is an iterative algorithm based on a combination of the Algebraic Recombination Technique (ART) and a curve fitting algorithm [3]. The distribution is fitted with exponential functions which provide the necessary smoothing. The ART component uses a nonrectangular pixel basis determined by the intersections of the observation lines, which simplifies the iterative corrections.

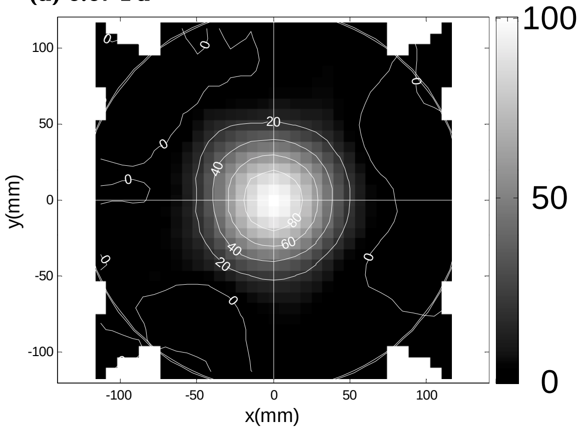
Experimental Apparatus

The new optical tomography sensor utilizes two separate lens array which observe the plasma at right angles, as seen in Fig. 1. The lines-of-sight of each optical arrays converge to a single point and spread out as a fan in the plasma. By locating the convergence point at the window, the necessary window diameter can be kept to a minimum. Alternately, the convergence point can be moved into the vacuum chamber to maximize the plasma volume sampled. Light from the plasma is focused by each lens in to a single fiber. The other end of the optical fibers are arranged into a rectangular array which is simultaneously imaged by a digital camera. Interference filters or etalons are placed between the optical fibers and the camera to select the desired wavelength of interest from the plasma. For the work presented in this paper, an interference filter centered at 750 nm was used as the wavelength selective element.

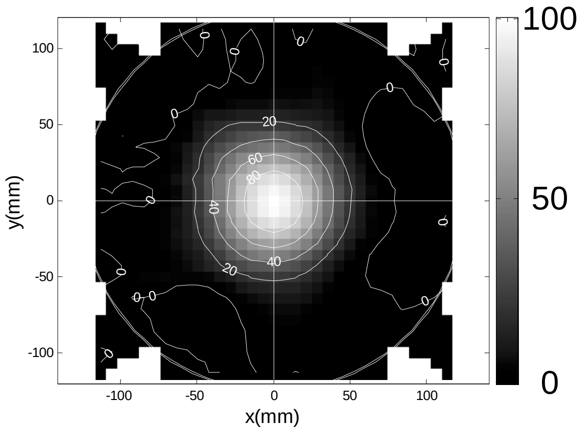
The optical tomography sensor is being tested on the ICP-GEC RF Reference Reactor [4]. This is a standardized plasma source designed to create plasmas similar to those found in commercial etching reactors. The plasma is created by a five turn flat coil which is insulated from the plasma by a quartz plate. The plasma source was modified with the addition of a quartz confinement ring, which helps extend the operating range of the plasma source [5]. The confinement ring is particularly useful when the cell is operated with electronegative gases such as SF_6 or CF_4.

The observation geometry of the tomography sensor has been chosen to optimize the coverage of the plasma in the ICP-GEC RF Reference Reactor. This geometry is shown in Fig 2. There are two fans of 41 fibers each. The lines-of-sight are separated by 2° and observe the plasma through 6 and 8 inch nominal diameter windows. Since the side arms supporting the windows are different diameters, the two arrays are located at different distances from the center of the plasma source. For the measurements presented in this paper, the tomographic measurements were made in a plane parallel to the lower electrode and containing the

(a) 6.67 Pa



(b) 0.26 Pa



(c) Difference (6.67 – 0.26 Pa)

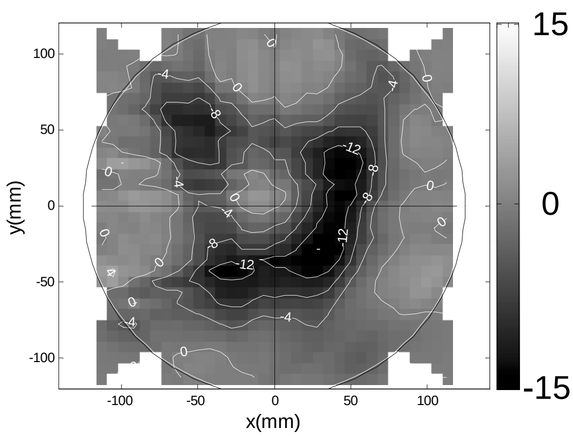


FIGURE 3. Normalized plasma distributions for 100W and 7.4 μmole/s (10 sccm) Ar at **(a)** 6.67 Pa (50 mT) and **(b)** 0.26 Pa (2 mT). The relative maximum intensities for (a) and (b) were 0.482 and 0.127 respectively. **(c)** is the difference between (a) and (b).

centers of the observation windows. This places the observation region approximately 5 mm above the lower electrode.

RESULTS

Typical plasma distributions found in the ICP-GEC RF Reference Cell are shown in Fig. 3. The finite pixel size and the actual wall geometry used with the Tikhonov regularization can be seen. In order to emphasize changes in the plasma uniformity, the maximum emisivity of each image has been normalized to 100. The quartz confinement ring helps reduce variations in the plasma distributions with varying plasma parameters and the differences between Fig 3a and Fig 3b are difficult to observe. Fig. 3c, which is the difference plot of the previous contour plots, clearly shows the changes to the plasma distribution as pressure is varied. The dark ring indicates that as the pressure is increased, the discharge radius decreases. This is probably due to collisions of charged particles with the neutral background gas. The nonuniformities in the ring are probably not real since similar distortions occur in all the difference plots and previous optical tomography measurements of argon discharges showed axially symmetric plasmas [6]. These distortions are probably either an artifact from residual systematic noise remaining from the sensor calibration procedure or distortions resulting from the observation geometry. Improvements in the calibration procedure are still ongoing. Apparent systematic calibration errors from fiber to fiber are still significantly larger than the statistical fluctuations of the measured signals.

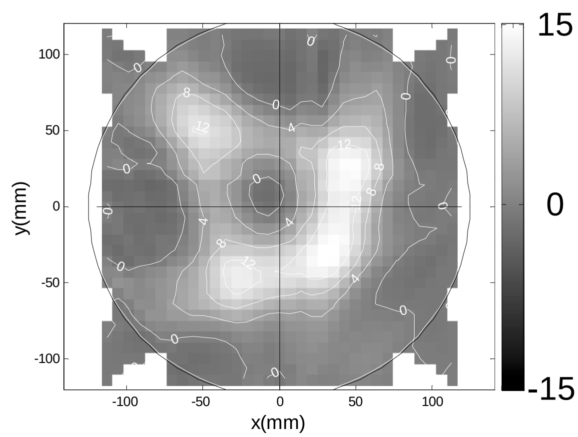


FIGURE 4. Difference between normalized plasma distributions at 250W and 50W with 1.33 Pa (10 mTorr) and 7.4 μmole/s (10 sccm) Ar. The relative maximum intensities for the original distributions were 0.513 and 0.117.

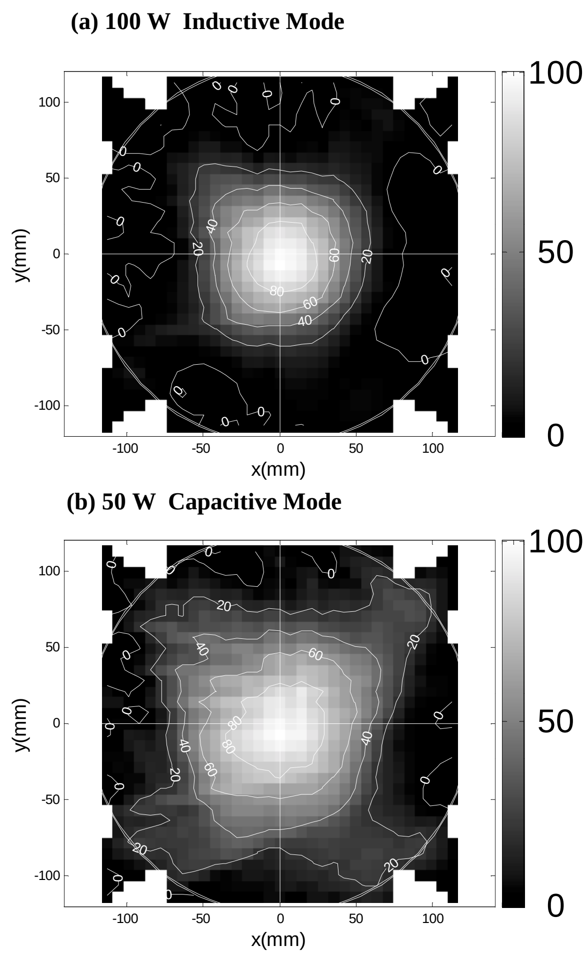


FIGURE 5. Normalized plasma distributions at 0.267 Pa with 1.5 µmol/s (2 sccm) Ar and 5.9 µmol/s (8 sccm) O_2 for **(a)** 100 W and **(b)** 50 W. This corresponds to an inductive and a capacitive plasma mode with respective relative maximum intensities of 0.017 and 7.25×10^{-4}.

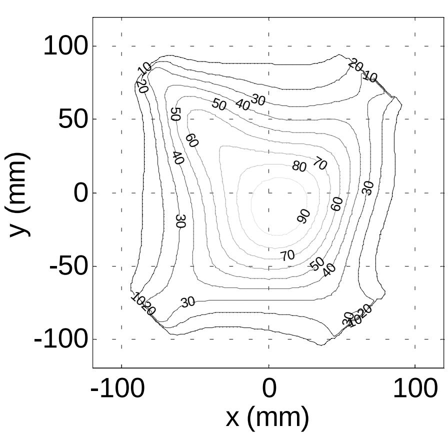


FIGURE 6. Tomographic inversion using the new iterative algorithm based on a combination of the Algebraic Recombination Technique (ART) and curve fitting algorithms. Plasma conditions are the same as Fig 5b.

Fig. 4 demonstrates the effects of plasma power on the plasma distribution. As might be expected, increasing plasma power increases the plasma radius.

Fig. 5 demonstrates the difference between inductive and capacitive plasma modes. The capacitive mode is found at lower powers and emits much less light. Use of an electrostatic shield between the coil and the dielectric vacuum interface significantly reduces the parameter range in which this type of discharge mode exists. Even with the Ar/O_2 discharge, the inductive mode shows a strong degree of radial symmetry. The capacitive mode diffuses over most of the plasma chamber. There appears to be increased optical emission along diagonals across the cell. This probably corresponds to increased current flow to the locations where the walls are closest to the center of the plasma. Fig 6 is from the same data as Fig 5b, except it was inverted using the new tomography algorithm.

CONCLUSION

A new optical tomography sensor has been demonstrated to be capable of monitoring changes in plasma uniformity with varying plasma conditions. This can be accomplished on a time scale and with a geometry suitable for use with many commercial plasma reactors. Research is still ongoing to reduce problems with systematic noise which seem to be currently limiting the accuracy of the distribution measurements.

REFERENCES

1. Buie, M. J., Pender, J. T., Soniker, J. Brake, M. L. , and Elta, M., J. Vac. Sci. Technol. A **13**, 1930-1934 (1995).
2. Benck, E. C., and Roberts, J. R., "Optical Computer Aided Tomography Measurements of Plasma Uniformity in an Inductively Coupled Discharge" in *Characterization and Metrology for ULSI Technology*, editied by D. G. Seiler et al., AIP Conference Proceedings 449, New York: American Institute of Physics, 1998, pp. 431-435.
3. Etemadi, K, and Benck E. C., manuscript in preparation.
4. Miller, P. A., Hebner, G. A., Greenberg, K. E., Pochan, P. D., and Aragon, B. P., J. of Res. of the Nat. Inst. of Standards and Technol. **100**, 427-440 (1995).
5. Hebner, G. A., and Miller, P. A., J. of Appl. Phys. **87**, 7660-7666 (2000).

6. Benck, E. C., and Roberts, J. R., "Optical Computer Aided Tomography for Plasma Uniformity Measurements" in *Proceedings of the Plasma Etch Users Group - The Fourth International Workshop on Advanced Plasma Tools and Process Engineering*, Sunnyvale, CA: Northern California Chapter, American Vacuum Society, 1998, pp. 8-13.